On the Origin of the "4686" Series.

By Thomas R. Merton, B.Sc. (Oxon.), Lecturer in Spectroscopy at University of London, King's College.

(Communicated by A. Fowler, F.R.S. Received March 25, 1915.)

[Plate 3.]

In recent years the class of spectrum lines known generally as the enhanced lines has become of especial importance in connection with their bearing on modern views as to the constitution of the atom. These lines were first investigated by Sir J. N. Lockyer, whose classical researches in this field have shown that a high order of energy is required for their production, and that they are especially conspicuous in many stellar spectra.

An important paper has recently been published by Fowler,* who has shown that the enhanced lines of the elements of the alkaline earth group can be arranged in series similar to those obtained in arc spectra, but that for these series Rydberg's constant N has to be replaced by the value 4N.

In 1896, Pickering† discovered in the spectrum of the star ζ Puppis a series of lines, which from their numerical relationship to the Balmer series were attributed to hydrogen, and which were considered by Rydberg‡ to be the Sharp series of hydrogen, the Balmer series being regarded as the Diffuse series. From the ζ Puppis series, Rydberg calculated the Principal series, the first line of which should have a wave-length of 4688 Å.U., and his conclusions were supported by the fact that a very strong line of about this wave-length was found to occur in the spectra of the nebulæ and certain stars.

Fowler§ subsequently observed the ζ Puppis series, and also a series the first member of which had a wave-length of 4686 Å.U., in vacuum tubes containing helium and hydrogen, which were excited by a strongly condensed electric discharge. Another series was also observed, the first member of which was at $\lambda = 3203$ Å.U., and which converged to the same limit as the 4686 series, being apparently a second Principal series. The three series were approximately represented by the formulæ

* 'Phil. Trans.,' A, vol. 214, p. 225 (1914)

† 'Astrophys. Journ.,' vol. 4, p. 369 (1896); vol. 5, p. 92 (1897).

‡ 'Astrophys. Journ.,' vol. 7, p. 233 (1899).

§ 'Monthly Notices, R.A.S.,' December, 1912.

ζ Puppis series $n = \mathrm{N}\left\{\frac{1}{2^2} - \frac{1}{(m+0{\cdot}5)^2}\right\}$, $m = 2, 3, 4 \ldots$

First Principal series $n = \mathrm{N}\left\{\frac{1}{1{\cdot}5^2} - \frac{1}{(m+1)^2}\right\}$, $m = 1, 2, 3 \ldots$

Second Principal series $n = \mathrm{N}\left\{\frac{1}{1{\cdot}5^2} - \frac{1}{(m+0{\cdot}5)^2}\right\}$, $m = 2, 3, 4 \ldots$

Fowler was unable to obtain these lines from hydrogen in the absence of helium, but the theoretical investigations of Rydberg appeared to justify the conclusion that the series in question were due to hydrogen.

Bohr* has developed a theory, involving the use of Planck's quantum hypothesis, by which he has arrived at formulæ for the series of lines emitted by an atom of the type investigated by Sir E. Rutherford.† On the assumption that the hydrogen atom consists of a central positive nucleus with a single electron moving around it, Bohr arrived at a formula which closely represented the Balmer series. Assuming further that the helium atom consists of a central positive nucleus with two electrons around it, Bohr found that the formulæ obtained closely represented the 4686 and associated series, and by introducing a small correction for the mass of the nucleus, the numerical agreement obtained was remarkably close. Bohr accordingly suggested that the lines in question were due to helium. According to Bohr's theory, the 4686 and 3203 series can be united into one, having a constant 4N instead of N, the correction for the mass of the nucleus involving a modified value of N, and the ζ Puppis lines being alternate members of a 4N series.

The theory has given rise to a considerable amount of theoretical discussion, into which it is not proposed to enter, but it involves the following assumption, with which the present investigation is concerned, namely, that the 4686 and ζ Puppis series owe their origin to helium, and are produced during the binding of an electron by a helium atom, from which two electrons have been removed by the exciting source.

Fowler‡ has come to the conclusion that the series in question are due to helium, from analogy with the 4N series of the alkaline earth metals, and has pointed out that the enhanced lines in general may possibly be explained in this manner, the arc lines being due to the binding of an electron by an atom from which only one electron has been removed.

This view constitutes a wide departure from the earlier hypothesis of the proto-elements, whose mass would probably be some simple fraction of the

* 'Phil. Mag.,' vol. 26, pp. 1, 476, and 857 (1913); vol. 97, p. 506 (1914).

† 'Phil. Mag.,' vol. 21, p. 669 (1911).

‡ *Loc. cit.*, 'Phil. Trans.'

parent atom, whilst the removal of two electrons from an atom would not appreciably affect the mass.

With regard to the origin of the lines, the spectroscopic evidence certainly points to helium. Evans* has observed the 4686 and associated series in vacuum tubes from which the hydrogen had apparently been completely eliminated, and Stark† has also observed the 4686 line in a helium tube showing no trace of the hydrogen lines. This evidence, however, is not conclusive. The extreme difficulty of preparing vacuum tubes free from hydrogen is well known, and the absence of hydrogen lines from the spectrum cannot be taken as conclusive evidence that hydrogen is not present. It is true that 4686 has not been observed in vacuum tubes containing pure hydrogen, but the same may be said of ultra-violet members of the Balmer series, which only appear in hydrogen tubes when helium is also present.‡ In the present investigation an attempt has been made to obtain some evidence of the nature of the atoms concerned in the production of the 4686 series.

The method adopted has been a determination of the highest order of interference of the spectrum lines at which the fringes, produced by the method of Fabry and Perot, remain visible. This depends on the widths of the spectrum lines, a problem which was first treated by Lord Rayleigh,§ and which has been the subject of quantitative investigation by Michelson.‖ The whole problem has recently been discussed by Lord Rayleigh.¶ It has been shown that the chief cause which determines the breadth of a spectrum line, produced in a gas at low pressure, is the Doppler effect due to the motions of the luminous particles in the line of sight. The limiting order of interference at which fringes may still be visible is given by the relation

$$N = K\sqrt{(M/T)},$$

where N is the limiting order of interference, K a constant, M the atomic weight of the luminous particle, and T the absolute temperature. The validity of this formula has been experimentally proved by Buisson and Fabry.**

If therefore a source of light, *e.g.* a vacuum tube, emits a radiation from an atom whose mass is known, it is possible to calculate the mass of an atom

* 'Nature,' vol. 92, p. 5 ; 'Phil. Mag.,' vol. 170, p. 284 (1915).
† 'Verh. d. Deutsch. Phys. Ges.,' vol. 16, p. 468 (1914).
‡ *Cf.* Liveing and Dewar, 'Roy. Soc. Proc.,' vol. 67, p. 467 (1900).
§ 'Phil. Mag.,' vol. 27, p. 298 (1889).
‖ 'Phil. Mag.,' vol. 34, p. 280 (1892) ; 'Astrophys. Journ.,' vol. 3, p. 251 (1896).
¶ 'Phil. Mag.,' vol. 170, p. 274 (1915).
** 'Journ. de Physique,' vol. 2, p. 442 (1912).

emitting another radiation, from a determination of the limiting orders at which these two radiations show interference fringes. The exact value of the constant K and the temperature T need not be considered. This method of determining the mass of an atom from the breadth of the spectrum lines has recently been applied by Buisson, Fabry, and Bourget* in their remarkable investigation of the Orion nebula. The validity of the formula is restricted to cases in which the radiations are produced in gases at low pressures, since, at higher pressures, broadening of the lines is also caused by disturbances depending on collisions between the luminous particles. Michelson (*loc. cit.*) has investigated the effect of pressure on the breadth of the lines, and his results show that at pressures as low as one-thousandth of an atmosphere the effect of collisions may be entirely neglected, and at a pressure of 5 mm. of mercury, the broadening due to this cause is still extremely small.

A vacuum tube containing helium and hydrogen at low pressure was excited by an induction coil, with a capacity of 0·0025 microfarad and a spark-gap in the circuit, the spectrum thus obtained consisting of helium lines, hydrogen lines, and 4686.

The pressure in the tube was very low, so that the glass walls fluoresced, the 4686 line appearing only outside the capillary, in accordance with the observations of Fowler.† A convergent beam of light from the vacuum tube was thrown by means of a lens on to the plates of a Fabry and Perot sliding interferometer, and the ring system was focussed by means of an achromatic lens on to the slit of the spectograph, which consisted of a large Hilger constant deviation spectroscope provided with a camera attachment. With this instrument a series of photographs could be taken on the same plate. The experiments were conducted as follows:—

The interferometer plates were set at a small difference of path and a photograph was taken. The difference of path was then successively increased and a series of exposures was made. From the series of photographs thus obtained the limiting order could be estimated. In estimating the limiting order, it will be seen that since on each exposure the order number increases with decreasing wave-length, it is usually possible (if the differences of path have been suitably chosen) to pick out some line in which the fringes are just visible. The determination cannot be made with a high degree of accuracy, but all the photographs taken have yielded concordant results.

In Plate 3, I shows a photograph taken through an étalon giving a

* 'Astrophys. Journ.,' vol. 3, p. 256 (1914).

† *Loc. cit.*, 'Monthly Notices.'

difference of path of 13 mm. It will be seen that the helium lines show sharp rings, whilst the 4686 line and the hydrogen lines show no trace of interference. The plates of this étalon were more heavily silvered than the plates of the interferometer, the fringes being, in consequence, more sharply defined. II shows a series of photographs taken with the interferometer, the differences of path being 2, 4, 12, 16, 20, and 24 mm. The lines at 4471, 4026, and 3889 are much over-exposed, and the fringes are consequently very indistinct. The limits of interference cannot be seen in the reproduction, but on the original plate fringes were just visible in 4686 at $\Delta = 4$ mm., and in helium ($\lambda = 4388$) at 24 mm. (The hydrogen lines are not visible on this plate.)

This gives

$$N_{4686} = \frac{4}{0{\cdot}0004686} \text{ and } N_{He} = \frac{24}{0{\cdot}0004388},$$

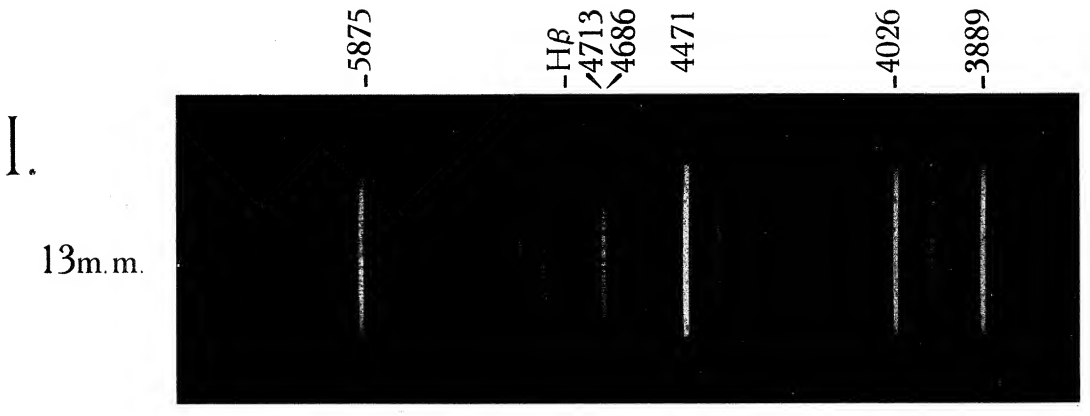
and for the mass of the system from which 4686 originates (He = 4),

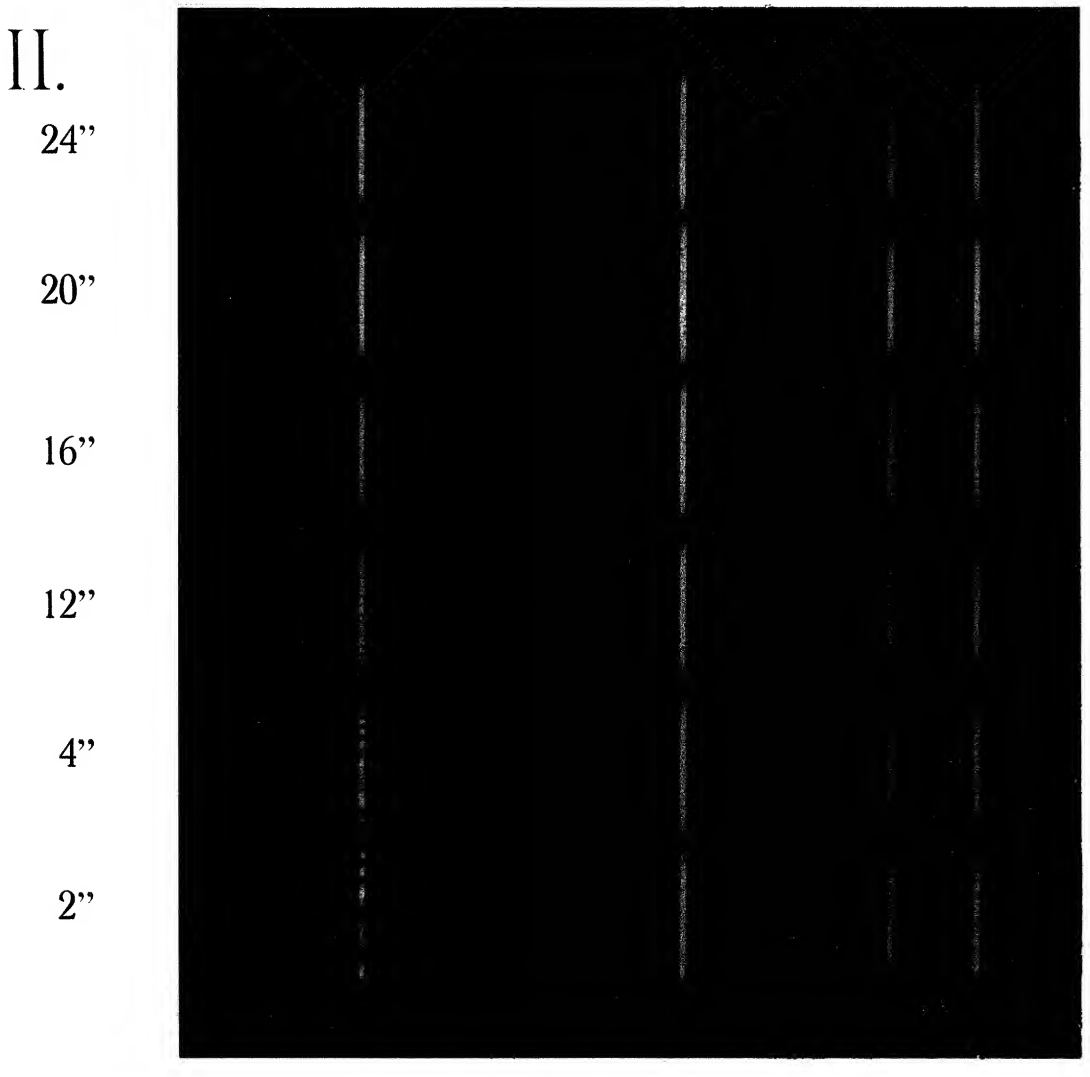
$$4 \times \left(\frac{4 \times 0{\cdot}0004388}{24 \times 0{\cdot}0004686}\right)^2 = \text{about } 0{\cdot}094,$$

or about one-tenth of the mass of the hydrogen atom.

It has been pointed out by Lord Rayleigh (*loc. cit.*) that Michelson's assumption that the temperature of the gas in an electrically excited vacuum tube is not very different from that of the walls of the tube has been amply confirmed by Buisson and Fabry (*loc. cit.*) in their determination of the change in the value of N when a discharge tube is immersed in liquid air. I have noticed, however, that in the case of the ordinary helium lines the value of N becomes smaller when capacity and a spark-gap are introduced, keeping the current through the primary of the coil unaltered. Buisson and Fabry (*loc. cit.*) state that under similar conditions broadening occurs in the lines of the Balmer series, but not in the lines of the secondary hydrogen spectrum, and they point out that this would indicate some special cause of broadening for the Balmer series. No mention is made of the pressure in the vacuum tubes at which this observation was made, and at low pressures even a feebly condensed discharge extinguishes the secondary spectrum.

Very little is known with regard to the origin of the secondary spectrum, and the broadening of the Balmer series and of the helium lines may possibly be explained as being due to the sudden rise of temperature at each impulse, but the above calculation might, by analogy, have no significance if the ordinary helium lines corresponded to the secondary hydrogen spectrum. This appears to be unlikely for several reasons. In particular, the solar chromosphere shows the Balmer series and the ordinary helium lines very

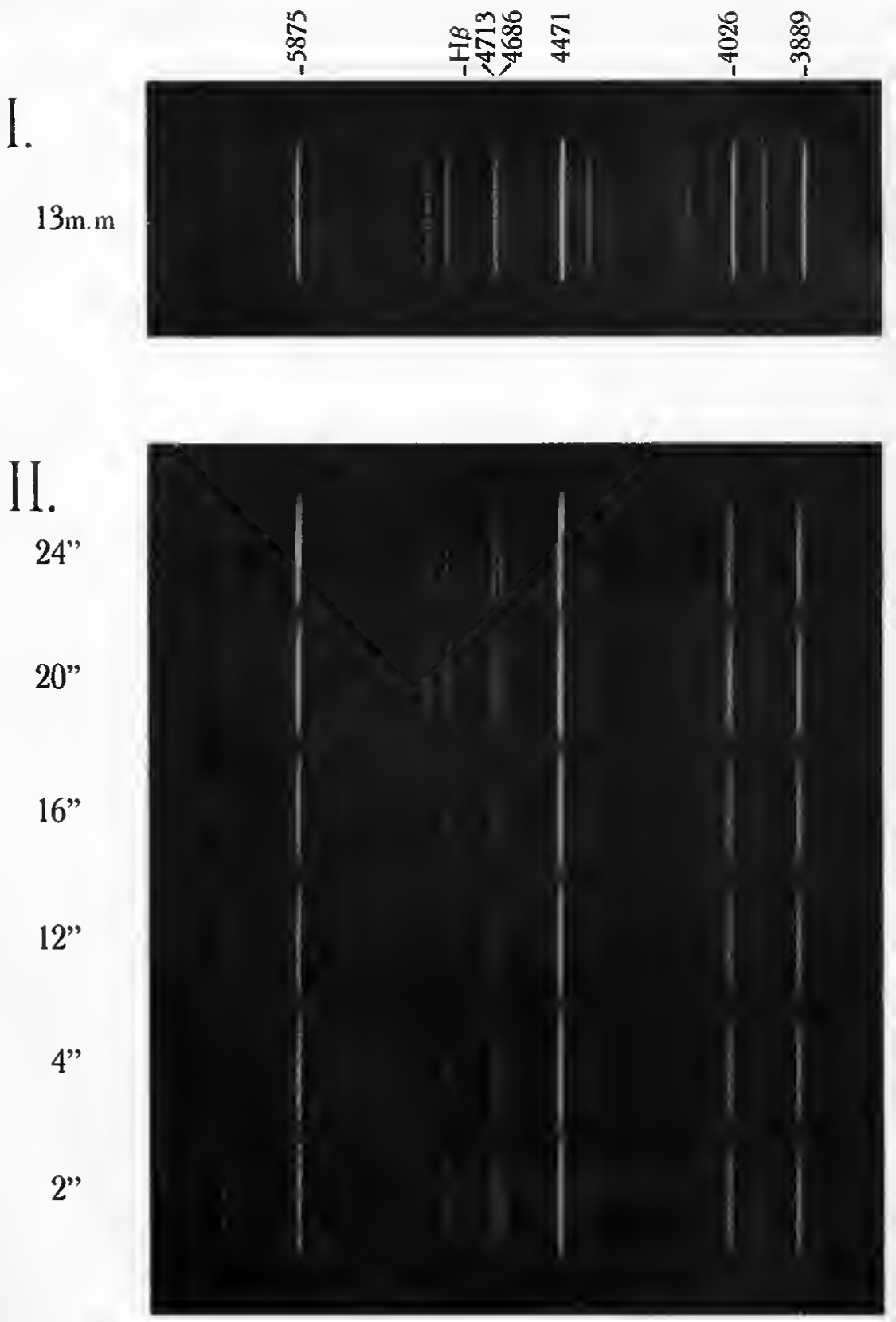

-5875
-Hβ
4713
4686
4471
-4026
-3889
I.
13m.m.


II.
24”
20”
16”
12”
4”
2”

strongly, but contains no trace of the secondary hydrogen spectrum. This would indicate that the ordinary helium spectrum and the Balmer series were analogous. On the other hand, however, in such experiments as those of King* the Balmer series behave as enhanced lines, a supposition apparently negatived by Fowler's (*loc. cit.*) demonstration that the Rydberg constant of enhanced series is 4N instead of N.

In any case the observed broadening with a condensed discharge would by itself appear to limit the use of the method employed to cases in which the radiations are produced simultaneously. Thus, in the case of argon, values of N have been found to vary in the red and blue spectra in the ratio of 7·5 to 1, but for the reason given above it is impossible to attach any quantitative meaning to the result. However, in the observations of 4686 and helium the spectra are produced simultaneously. It is possible that this method of calculating the mass of the luminous particles may not be applicable to the enhanced lines, the breadth of which may be controlled by circumstances at present unknown, but if the method is valid in such cases, the results would indicate that the 4686 line is due to systems of subatomic mass.

* 'Astrophys. Journ.,' vol. 38, p. 315 (1913).


5875
Hβ
4713
4686
4471
4026
3889
I.
13m.m
II.
24”
20”
16”
12”
4”
2”